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Parameterization of Hysteresis Effects in Accumulator Quadrupole Magnets

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Abstract

The hysteresis curves of two Accumulator sample magnets have been measured, one 'large' quadrupole and one 'small' quadrupole. Based upon these measurements, a parameterization of hysteresis effects is deduced and generalized to other magnets. The goal is to incorporate the best knowledge of the magnets we have into the Accumulator model, on which lattice measurements are based and which is used to calculate an accurate first guess at the E-835 deceleration tables. Since a well-defined sequence of current cycles is performed during Accumulator operations, some simplifying hypotheses can be applied.

1 Magnet measurements

The two magnets measured at the Magnet Test Facility (MTF) were LQD-001 (a 'large' quad; the LQD family is placed in position 11 of each sector) and SQC-162-1 (a 'small' quad; this family of magnets is found in positions 3, 6 and 7). Reference [1] describes these magnets in detail.

The raw data can be found in the spreadsheet file Y:/projects/ Pbar Magnets/Quad Excitation Summary.xls on Beamssrv1/pbar.bd (Windows NT Beams domain) or on the MTF web page at http:// tdpc01.fnal.gov/pbar-magnets.

The data are also plotted in Figure 1. The blue and cyan curves correspond to the up and down ramps, respectively. The other curves represent measurements taken starting from intermediate set points.

In order to make the hysteresis curves distinguishable from each other, the vertical axis is the integrated field gradient minus a linear term:

$$(\text{y axis}) = (\text{integrated gradient}) - (\text{current}) \times (\text{arbitrary constant}).$$

Eight intermediate curves were measured for the SQC-162-1 magnet, and two for LQD-001.

2 Hysteresis parameterization

A magnet's excitation characteristics are schematically represented in Figure 2. The field at zero current can be arbitrarily reduced by exciting hysteresis cycles of decreasing amplitude. After such procedure, an up ramp u will start from the origin and continue into the saturation region, where the up and down ramps coincide. Ramping the current down to zero will delineate the down ramp d, which leaves a remnant field at zero current. A successive up ramp u^* will start from this remnant field, but will soon merge with the previous up ramp u.

Before each deceleration, the buses and shunts are cycled from their set value to zero and back three times. This procedure has been determined empirically to ensure reproducibility of initial conditions. This implies that magnet strengths follow the curves y and u^* between $i = 0$ and $i = i_0$, i_0 being the set value. During deceleration, the magnet strengths will be on the curve y, which depends on the current i and on the set point i_0.

This so-called interjacent curve $y(i, i_0)$ is expressed as a function of

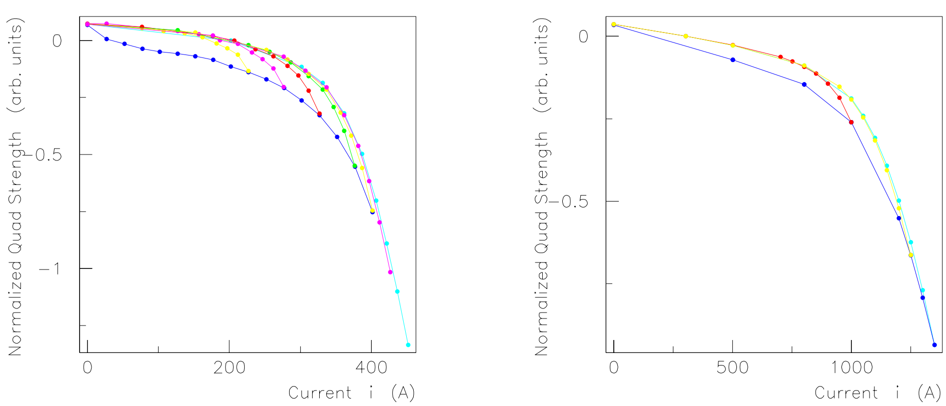

Figure 1: Measurements of hysteresis for magnets SQC-162-1 (left) and LQD-001 (right).

up ramp $u(i)$ and down ramp $d(i)$:

$$y = \alpha\, u + (1-\alpha)\, d \qquad\qquad \text{with } 0 \leq \alpha \leq 1.$$

The parameter $\alpha(i, i_0)$ is chosen to summarize hysteresis effects.

In order to measure α, the up and down ramps are fitted with an 8th-degree polinomial (Figure 3). This fit is necessary because up ramp, down ramp and interjacent curves were measured at different currents. Since the data outline u^* instead of u, but there is not enough information to distinguish the two, the up ramp fit is constrained to pass through the origin and the first up-ramp data point is discarded. The goodness of the fit can be judged by plotting the difference of the resulting curves $u(i)$ and $d(i)$ (Figure 4), which closely resembles the measured one (as seen in Reference [1], for instance). The χ^2 is not a good indicator because the degree of the polinomial is purposely chosen to be close to the number of data points; also, the errors on the measured integrated gradient are not well known.

Once the functional form of $u(i)$ and $d(i)$ is well approximated, it is possible to turn a set of N measurements of current and gradient $[i_k, y(i_k, i_0)]$, $k = 1, \ldots, N$ along the interjacent curves for a given set current i_0 into measurements of $\alpha(i_k, i_0)$:

$$\alpha(i_k, i_0) = \frac{d(i_k) - y(i_k, i_0)}{d(i_k) - u(i_k)}.$$

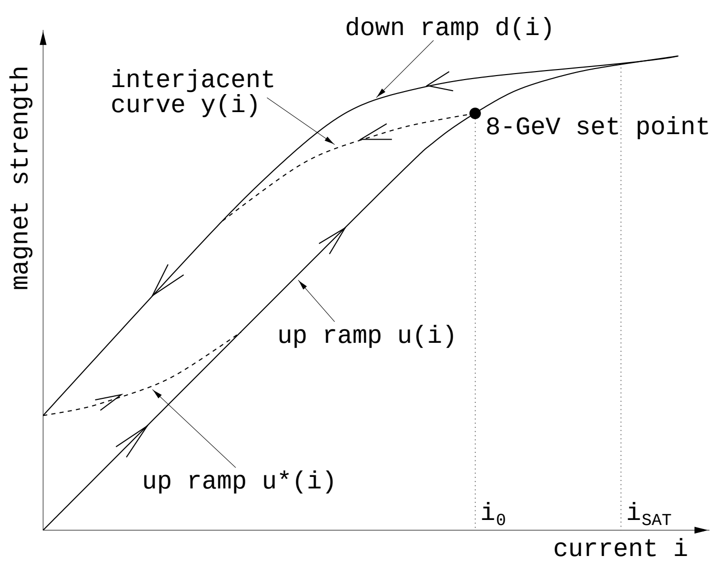

Figure 2: Schematic representation of excitation curves.

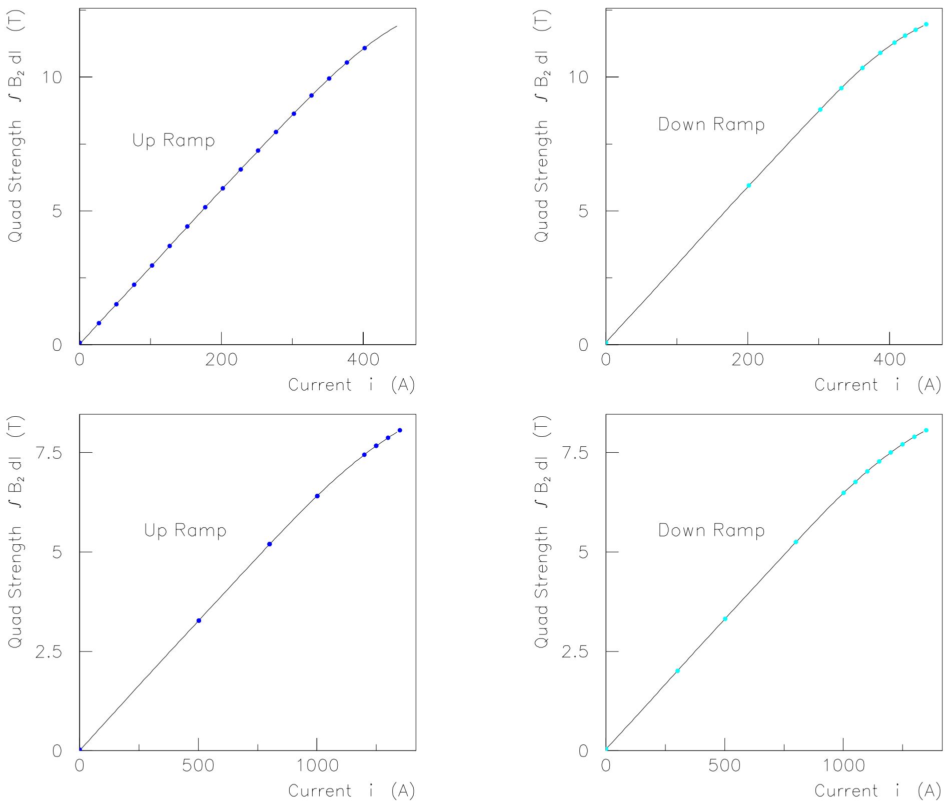

Figure 3: Fits of up and down ramp data for the SQC-162-1 (above) and the LQD-001 (below) magnets. B_2 is the field gradient $\partial B_y/\partial x$.

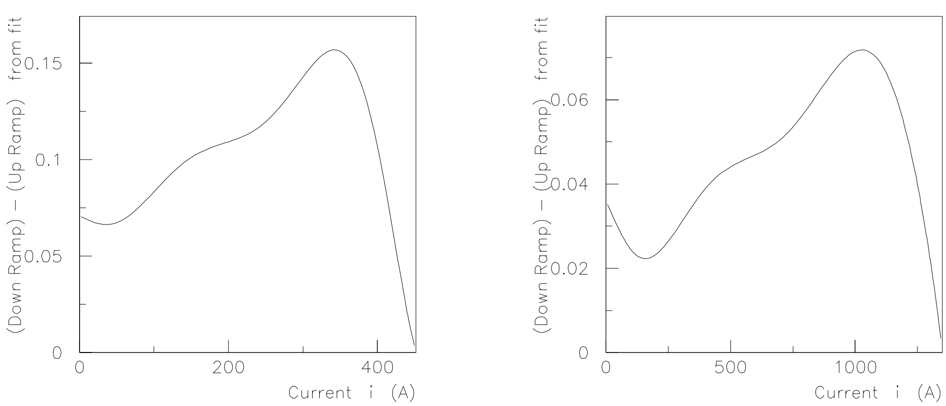

Figure 4: The difference of the fitting functions $d(i) - u(i)$ for SQC-162-1 (left) and LQD-001 (right).

The behavior of α as a function of current for various set points is shown in Figures 5 and 6. It should be noted that both measurement uncertainties and the fitting procedure contribute to the deviations of α from a smooth function bound between 0 and 1.

Remarkably, in this regime, α is well represented by the following functional form:

$$\alpha(i, i_0) = \exp\left[\frac{i - i_0}{\iota}\right] \qquad (i < i_0).$$

For each value of i_0, a fit is performed with equal weights for each point; ι is left free to vary. Fortunately, ι, which will be called the interjacent-curve characteristic parameter, turns out to be, for a single magnet, nearly independent of i_0, as shown in Figure 7. This is especially true if one considers that 8-GeV settings do not vary by much, even if the lattice is changed (the present settings for LQD magnets is about 1215 A; the SQC magnets run at about 250 A). Also, ι appears to be a fixed fraction of the saturation current i_{sat} (defined as the smallest current for which $u = d$), for both magnet types:

$$\frac{\iota^{(\text{SQC})}}{i_{\text{sat}}^{(\text{SQC})}} = \frac{25\ \text{A}}{450\ \text{A}} \simeq \frac{\iota^{(\text{LQD})}}{i_{\text{sat}}^{(\text{LQD})}} = \frac{70\ \text{A}}{1300\ \text{A}} \simeq 5\%.$$

Since all families of small quads have similar saturation currents, and the same is true for large quads, one can assume that $\iota^{(\text{SQC})}$ applies to all small quads, and $\iota^{(\text{LQD})}$ to all large ones. Of course, this generalization is approximate, but it is the best one can do given the measurements we have.

3 Concluding remarks

An Accumulator model has been implemented with an analytic (even though approximate) description of hysteresis effects relevant to E-835 decelerations. The corresponding MAD file can be found on the Beam Physics Unix cluster (aka 'cartoon' cluster), in the file ~stancari/lattice/ramps/devel/QUAD_EXCITATION.DAT, which is read by the the main model, ACC_UPGRADE.lat. This model is used for measuring the lattice (the 'fudge factors' in particular) by fitting the quad strenghts to the 1-bump closed-orbit measurements. It is also used for calculating the ramp tables for deceleration. These represent the best guess at the Accumulator behavior and are corrected during ramp development to match the lattice requirements (tunes, chromaticity, transition energy, ...). Ramp development itself will be described in another note.

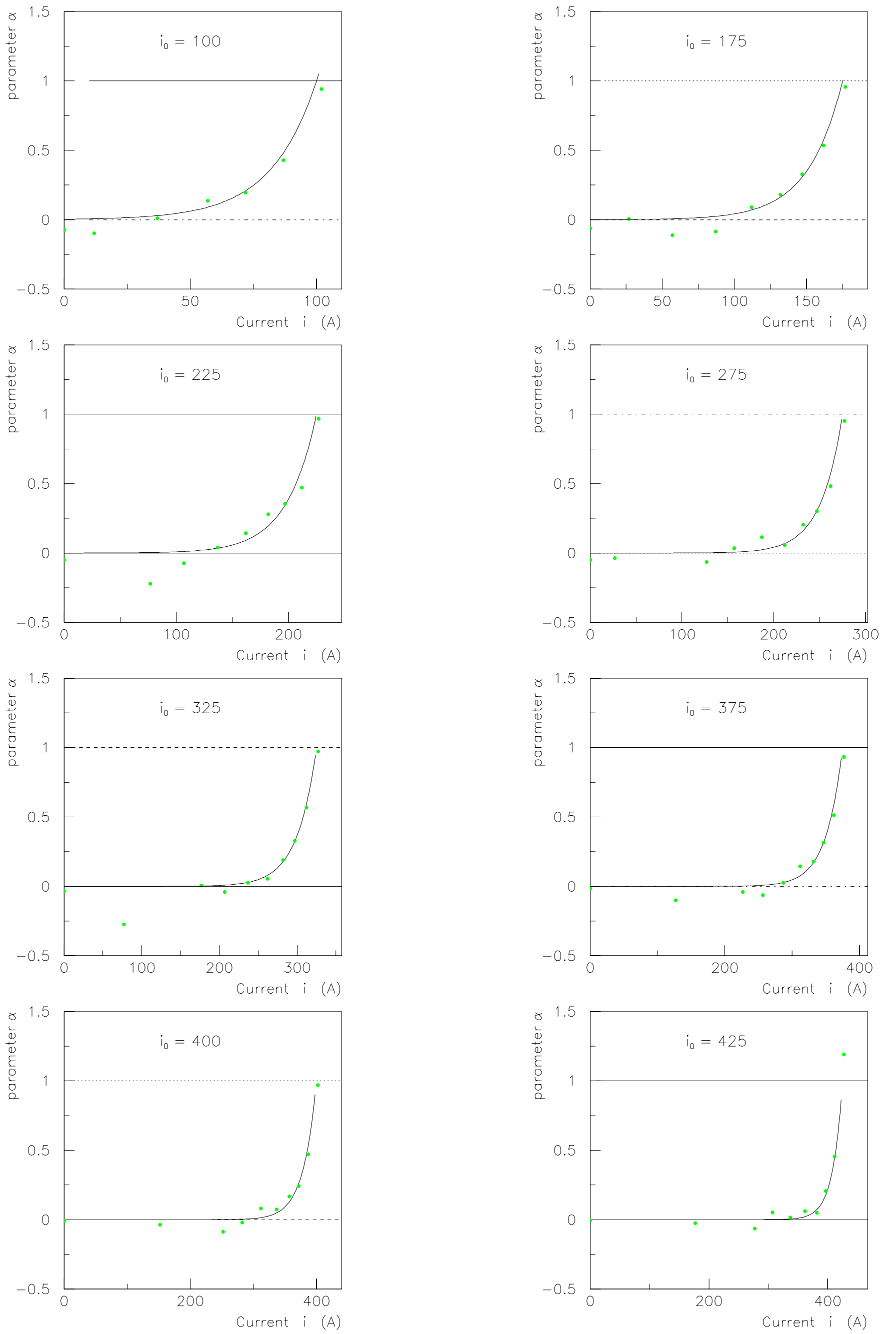

Figure 5: The parameter α as a function of i for different values of i_0 (magnet SQC-162-1).

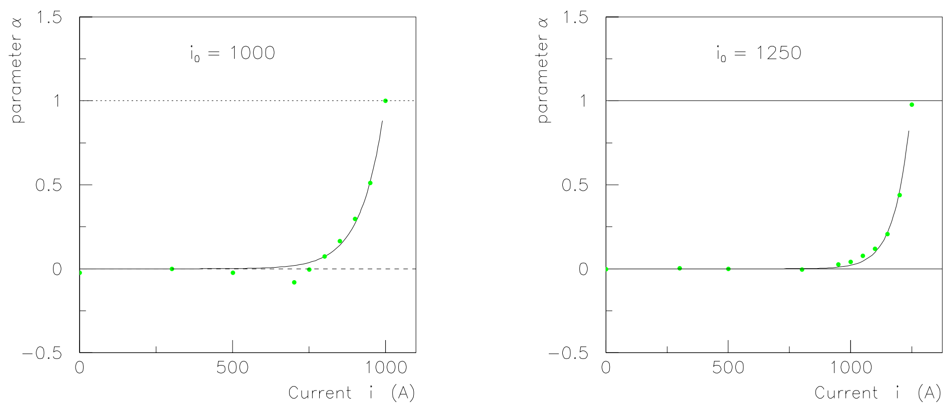

Figure 6: The parameter α as a function of i for different values of i_0 (magnet LQD-001).

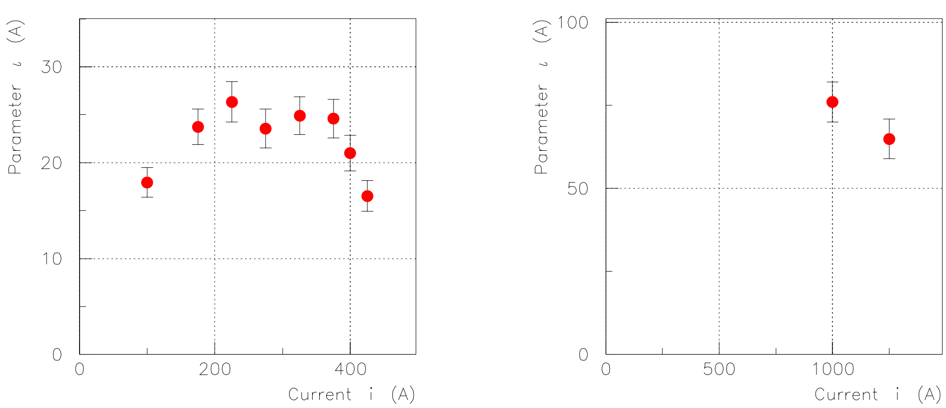

Figure 7: The interjacent-curve characteristic parameter ι as a function of i_0 for the SQC-162-1 (left) and the LQD-001 (right) magnets. The errors come from the fits.

4 Acknowledgements

I wish to thank Dr. B. Brown for the interesting discussions and for providing some relevant references on the subject of hysteresis. Dr. S. Werkema's help was indispensable for the interpretation of the data; he also shared the preliminary analysis he had performed on it.

References

[1] B. C. Brown. *Some results on Tev I quadrupole magnet strengths*, P-Bar Note 569, September 1997.